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Results from 2002 and 2009 Silene Criticality Dosimetry Intercomparisons

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1 Introduction

The external dosimetry program has participated in two intercomparisons conducted at the Silene facility in Valduc, France in 2002 and 2009. During the 2002 test the dosimeters (beta/gamma and neutron) were mailed to the facility and returned following the test. In 2009 a representative was present during testing and observed irradiation locations and conducted additional measurements. This report reviews the testing procedures, preparations, irradiations, and presents results of the two tests. Derivations of the spectral correction factors for neutron TLDs are also provided.

2 Facility Description

The Silene reactor is located at the CEA Valduc Center in Is-sur-Tille, France. The uranyl nitrate reactor is operated in one of three modes: pulse, free evolution, or steady state. In pulse mode the reactor is initiated by quickly removing control rods and the reaction is ceased by the creation of bubbles in the solution at which time the fissile solution is drained to holding tanks. In free evolution mode the reactor is operated in a series of pulse modes by retaining the solution in the reactor instead of immediately draining it following a burst. In steady state the reactor is operated at low power for up to 30 minutes. The reactor is a homogeneous assembly located in a large (12 X 19 m) concrete cell. The core is a small orthocylindrical vessel (360 mm diameter) containing the fissile solution.

The reactor can be operated either in the "bare" configuration or with a 10 cm lead shield surrounding the core to provide a higher neutron to photon dose ratio. The introduction of the lead will not significantly affect the neutron spectrum but does dramatically decrease the photon flux emitting the complete assembly. A schematic of the Silene irradiation cell is given in Figure 1. Figure 2 shows the reactor with lead shield partially removed and Figure 3 shows a typical test irradiation arrangement.

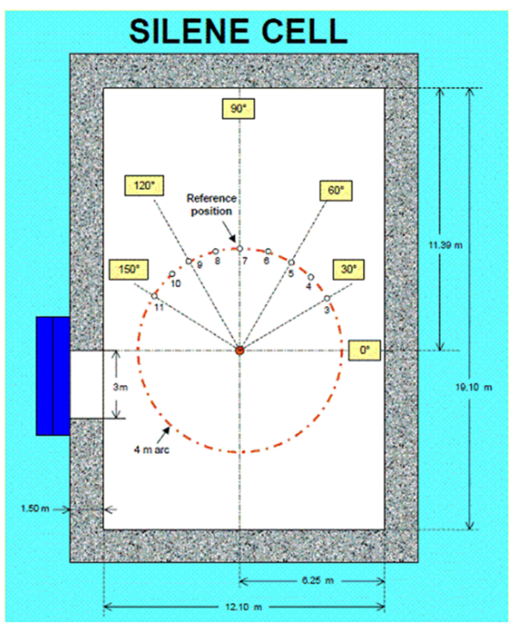

Figure 1: Plan view of the Silene irradiation cell showing the reactor location and reference irradiation positions.

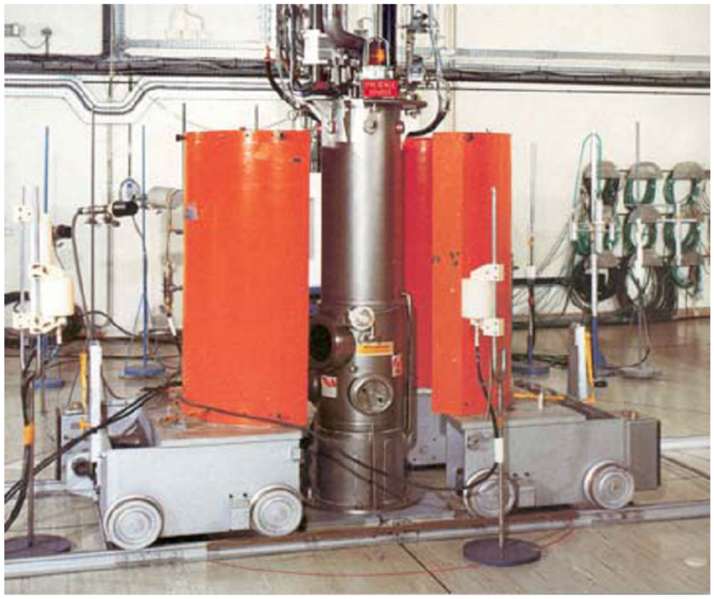

Figure 2: Silene reactor with lead shield partially removed.

Figure 3: Typical irradiation geometry for test dosimeters. Source-to-phantom distance is 4 m.

3 2002 and 2009 Irradiations

Three irradiations were performed during the 2002 and 2009 intercomparisons. In 2002 the tests included a free evolution (FE) cycle with bare reactor core, a steady-state (SS) irradiation with lead shielded core, and a free evolution irradiation with lead shielded core. The 2009 tests were all pulsed irradiations with the first being a lead shielded exposure and the second and third irradiations with the unshielded reactor. Irradiations were performed on 10/13/2009, 10/14/2009, and 10/15/2009.

Following the irradiations the Silene staff determines the total number of fissions for an irradiation and calculates the reference delivered doses at various distances. The 2002 reference doses are listed in Table 1. All irradiations were performed at four meters from the reactor.

Table 1: Reference Doses for 2002 Intercomparison. The neutron dose, D_n includes contributions from both proton recoils and heavy charged particles. The incident gamma dose, D_γ, is a result of prompt photons emitted from the reactor. The dose from photons that are created inside the phantom are treated separately and reported as $D_{n,\gamma}$.

Irradiation	Mode	Shield	D_n (Gy)	$D_{n,\gamma}$ (Gy)	D_γ (Gy)
1	FE	None	1.83	0.54	2.49
2	SS	Pb	0.85	0.27	0.14
3	FE	Pb	1.80	0.57	0.30

At this time the reference delivered doses for the 2009 test are not available.

A short discussion on the method of reporting dose quantities is in order. The most common and accepted method for reporting personnel doses are in keeping with the recommendations of the International Commission on Radiation Protection (ICRP). The quantities reported for determining compliance with protection quantities are approximated using operational quantities defined by the International Commission on Radiological Units and Measurements (ICRU). In general, personnel doses are reported according to the quantity Personal Dose Equivalent, $H_p(d)$, where d is the depth at which the dose equivalent is determined and is 10 mm for penetrating radiations [1, 2, 3]. For accident doses the quantity of interest is the absorbed dose. Since personnel dosimeters are routinely calibrated in terms of the personal dose equivalent the absorbed dose calculations can be found by removing the modifier used to account for long term stochastic risk (e.g. the quality factor). In this case, the reported dose is referred to as the Personal Absorbed Dose, $D_p(10)$. It is common practice to apply dose conversion coefficients to convert a physical quantity such as fluence to the various dose or dose equivalent quantities. The assumptions used in the determination of these conversion coefficients (DCFs) is critical to properly comparing dose values. Neutron conversion coefficients [3, 4, 5, 6, 7] are typically calculated under specific irradiation conditions such as an aligned and expanded field. The total conversion coefficient for a given energy region (bin) is the sum of the first collision dose (proton recoil and heavy charged particle dose) and the dose from photons created inside the phantom. Thus, the neutron conversion coefficients include the contributions from columns four and five in Table 1. This can lead to discrepancies when comparing "neutron and photon" doses since the Valduc operations often reports the photon dose as the sum of the incident photon (D_γ) and the secondary gamma ($D_{n,\gamma}$) dose.

During 2002 testing whole body beta/gamma and neutron TLDs were tested at four meters from the reactor. Sufficient controls/transits were included to allow for determination of additional signal due to natural background as well as screening x-rays incurred during shipment. In 2009 beta/gamma and neutron TLDs were tested as well as a recently introduced fixed nuclear accident dosimeter (FNAD) [8]. Additionally, humanoid phantoms were provided that contained the Reference Man [9] levels of sodium by weight. One phantom was irradiated during the first excursion and the other in the second pulse. Simulated blood sodium readings were performed using the Identifinder [10]. Whole body (neutron and photon) dosimeters were irradiated at 2, 4, and 6 meters from the reactor while FNAD and sodium-water phantoms were positioned at a distance of four meters.

Activation foils (two sets per FNAD irradiation) were included. The counting of these foils is normally performed using the high purity germanium (HPGe) detectors in the Y-12 lung counter. For this test the counts were performed at Silene by LLNL staff using a portable HPGe detector. Since different detectors were used and since no Y-12 calibration sources were available for cross reference this count data is of limited value to Y-12 at this time. However, it may be possible to request LLNL count Y-12 sources and thus be able to, at some level, predict the count rates had the foils been counted at Y-12. Additionally, no hot plate or fume hood was available to burn the sulfur tablets. Instead, the tablets were crushed and counted by LLNL staff.

Between the 2002 and 2009 tests changes were made to the type of TLD used for beta/gamma dosimetry. These changes included a different TLD card as well as changes to the source used for reader calibration. Both dosimeter types successfully completed DOELAP performance testing and were accredited for personnel monitoring.

4 Absorbed Dose Calculations

4.1 2002 Intercomparison

The card sensitivity, element correction coefficient (ECC), and reader sensitivity, reader calibration factor (RCF) corrected TLD readings from the 2002 intercomparison are listed in Table 2. The anneal and read dates for all TLDs were 03/28/2002 and 08/08/2002, respectively. The calculated fade was determined to be 0.79. These results were processed through the beta/gamma algorithm and supralinearity corrections were applied according to total signal. The computed doses are included in Table 2

Table 2: Beta/Gamma TLD readings from 2002 intercomparison. All TLD results have been corrected for RCF and ECC. Fade was determined to be 0.79 but was not applied to the results listed here.

Irradiation	Mode	Shield	EL1 (mR*)	EL2 (mR*)	EL3 (mR*)	EL4 (mR*)	Dose (Gy)
1	FE	None	168125	181592	187826	11437356	2.15
1	FE	None	166651	168879	200093	10248816	1.85
1	FE	None	171176	194665	182564	9390744	1.97
1	FE	None	163667	180925	187348	11369906	2.09
2	SS	Pb	27089	31919	47988	5006133	0.26
2	SS	Pb	22603	25353	33497	6018812	0.23
2	SS	Pb	26621	30080	31903	5350880	0.35
3	FE	Pb	64122	69827	87999	12763187	0.69
3	FE	Pb	62758	72315	79575	12007520	0.80
3	FE	Pb	43250	51861	66694	12493058	0.46

Neutron doses were determined by folding calculated leakage rates from the shielded and unshielded reactor with energy response functions reported elsewhere [11]. This was necessary since the neutron spectral correction factors which correct for response and dose for various energy spectra were available for the facility. Spectra which were assumed to be reasonably similar (Sheba, HPRR with polyethylene shield, etc.) were used as comparisons. The calculated dose equivalent values reported from these representative spectra were modified by an assumed average spectrally-weighted quality factor of 10. The neutron TLD readings (ECC and RCF corrected) are listed in Table 3.

The calculated doses for the three excursions were determined to be 1.2 Gy, 0.5 Gy, and 1.2 Gy. The reported versus reference doses and the bias for each are listed in Table 4.

The average bias in neutron dose for the three irradiations was -51% which would fail testing criteria recommended in the draft ANSI N13.3 [12]. However, the bias is consistent indicating that

Table 3: Neutron TLD readings from 2002 intercomparison. All TLD results have been corrected for RCF and ECC. Fade was determined to be 0.79 but was not applied to the results listed here.

Irradiation	Mode	Shield	EL1 (mR*)	EL2 (mR*)	EL3 (mR*)	EL4 (mR*)
1	FE	None	4905134	214461	209109	10288794
1	FE	None	5323944	228038	200045	10766773
1	FE	None	6400443	247411	231498	11977543
1	FE	None	6381455	251449	212478	10713338
2	SS	Pb	3042067	62364	36695	5468135
2	SS	Pb	3355505	64246	34619	5721054
2	SS	Pb	3088820	59670	36237	4628363
3	FE	Pb	7773988	135857	79329	11472434
3	FE	Pb	6449566	134610	65230	10576420
3	FE	Pb	7095667	131103	72289	13006926

Table 4: 2002 intercomparison results for photon and neutron doses.

Irr.	Mode	Shield	D_n Ref. (Gy)	D_n Rep. (Gy)	% Bias D_n (%)	D_γ Ref. (Gy)	D_γ Rep. (Gy)	% Bias D_γ (%)
1	FE	None	2.37	1.2	-49	2.49	2.0	-20
2	SS	Pb	1.12	0.5	-55	0.14	0.3	53
3	FE	Pb	2.37	1.2	-49	0.30	0.6	100

the spectral correction factors were computed correctly to account for spectral response and average delivered dose per neutron, but were either incorrectly scaled for light output per reaction in the TLD element or the leakage spectra from the reactor was inaccurate. More troubling is the bias in photon dose which ranged from -20% to +100%. Since the photon doses were calculated using the DOELAP-accredited algorithm no changes can be recommended unless a criticality-specific algorithm is developed.

4.2 2009 Intercomparison

4.2.1 Whole Body TLD Results

The card sensitivity, element correction coefficient (ECC), and reader sensitivity, reader calibration factor (RCF) corrected TLD readings from the 2009 intercomparison are listed in Table 6. The anneal dates for all TLDs was 09/21/2009 and the neutron TLDs were processed on 12/22/2009 while the HBGT TLDs were read on 12/28/2009. The calculated fade was determined to be 0.82. These results were processed through the beta/gamma algorithm and supralinearity corrections were applied according to total signal. The computed doses are included in Table 2.

Neutron absorbed doses were calculated using spectral correction factors derived from the provided 2002 reference doses and average TLD readings. The SCFs could only be determined for 4 m distance and were not modified to account for room and air scatter effects at lesser or greater distances. The correction factors determined using the 2002 reference results and TLD readings are listed in Table 5. Neutron TLD readings and doses are listed in Table 7.

Table 5: Silene neutron spectral correction factors calculated using the 2002 reference doses and TLD readings at 4 m. These SCFs include the light output per reaction rate and report the absorbed dose in rad.

Spectrum	CF_{Cd}	CF_{Pl}
Silene (Bare) 4m	0.034	0.018
Silene (Pb) 4m	0.028	0.017

4.2.2 FNAD Results

The FNAD was irradiated at 4 m from the reactor during each of the three excursions. The TLDs were annealed on 09/15/2009 and read on 12/29/2009. The TLD results were corrected for fade, ECC, and RCF and a conversion of 25400 gU/rad applied to the net neutron signal. Since the prototype FNAD was used no incident photon doses were measured. The TLD results from the three tests are listed in Table 8 and the calculated ambient absorbed doses, $H^*(10)$, are given in Table 9.

4.2.3 Blood Sodium Measurements

Water filled humanoid phantoms with Reference Man levels (by weight) of sodium were irradiated during the first and third excursions. The preliminary estimates of neutron absorbed dose (determined following the conclusion of the intercomparison exercise) were used and decay corrected for the various measurement times post irradiation. The Identifinder confidence in detecting Na-24 is listed in Table 10 along with the decay corrected absorbed dose. Count durations were varied in an attempt to demonstrate the detection capability of the instrument as well as to simulate spectra taken following lower delivered doses.

Table 6: Beta/Gamma TLD readings from 2009 intercomparison. All TLD results have been corrected for RCF, ECC, background, and fade.

Irr.	Shield	Dist. (m)	EL1 (gU)	EL2 (gU)	EL3 (gU)	EL4 (gU)	Photon Dose (Gy)	Neutron Dose (Gy)
1	Pb	2	191630	224933	276581	43246667	1.64	7.35
1	Pb	2	238926	280427	354396	63133785	1.98	10.73
1	Pb	2	203205	185509	253060	40153847	1.58	6.82
1	Pb	2	233484	233878	304573	41234591	1.88	7.00
1	Pb	4	79019	88783	96168	16968388	0.72	2.88
1	Pb	4	80623	93860	112735	14096684	0.74	2.39
1	Pb	4	108506	128671	132653	19195098	0.99	3.26
1	Pb	4	83787	96720	119155	17996051	0.75	3.06
1	Pb	6	51874	53930	69168	9148130	0.45	1.55
1	Pb	6	49951	55239	68780	8556799	0.44	1.45
1	Pb	6	52967	54622	63570	10245304	0.48	1.74
1	Pb	6	65600	75662	77707	8649394	0.60	1.46
2	None	2	423735	468896	533445	15334754	3.27	2.69
2	None	2	437565	481920	552797	16302259	3.32	2.86
2	None	2	450468	458702	498472	18311828	3.23	3.22
2	None	2	461019	504934	613859	27797415	3.28	4.92
2	None	4	114989	132684	141329	5205302	1.05	0.92
2	None	4	119140	133136	147534	5541393	1.08	0.98
2	None	4	117551	131340	161371	5519449	1.06	0.97
2	None	4	124967	143140	161273	7323122	1.18	1.30
2	None	6	58563	64429	73320	3553891	0.58	0.63
2	None	6	53345	59109	64966	2967393	0.49	0.52
2	None	6	65875	68743	76328	4075804	0.60	0.72
2	None	6	58376	63242	70834	3566417	0.53	0.63
3	None	2	1470435	1508088	1782731	59524481	9.37	10.46
3	None	2	1379738	1536281	1640891	56319231	8.84	9.90
3	None	2	1483311	1685037	2005618	68194707	9.65	12.02
3	None	2	1474030	1512395	1766017	71318089	9.39	12.58
3	None	4	363852	381512	406861	17258350	2.82	3.04
3	None	4	356953	374392	429271	18977389	2.78	3.35
3	None	4	354233	366984	450357	19784225	2.75	3.50
3	None	4	390819	404313	464671	23028515	2.95	4.08
3	None	6	170884	185640	208750	10965507	1.48	1.94
3	None	6	184194	206399	236545	13606490	1.71	2.42
3	None	6	184907	209803	198612	13329136	1.60	2.37
3	None	6	177577	185061	206072	11604689	1.54	2.06

Table 7: Neutron TLD readings from 2009 intercomparison. All TLD results have been corrected for RCF, ECC, background, and fade.

Irradiation	Shield	Dist. (m)	EL1 (mR*)	EL2 (mR*)	EL3 (mR*)	EL4 (mR*)	Dose (Gy)
1	Pb	2	22241510	571831	254095	28084196	5.31
1	Pb	2	29341691	508012	209469	38008039	7.13
1	Pb	2	20863396	480383	272905	30771730	5.35
1	Pb	2	28698017	619056	256864	36149757	6.87
1	Pb	4	8891996	202841	101201	12179535	2.21
1	Pb	4	10346434	211522	107219	14308929	2.58
1	Pb	4	8806121	212707	105817	12877818	2.25
1	Pb	4	8758259	195929	98887	13446650	2.29
1	Pb	6	5443337	129680	65872	8420107	1.43
1	Pb	6	4345736	117814	63482	6502667	1.12
1	Pb	6	5149938	119448	56281	6762935	1.25
1	Pb	6	4561967	118126	53773	6814719	1.18
2	None	2	10568050	536990	474226	14042339	2.89
2	None	2	12468533	608797	526377	17007888	3.46
2	None	2	8626097	576402	514894	13317818	2.49
2	None	2	8082705	531987	493049	11604157	2.26
2	None	4	3433383	153729	151354	5041403	0.99
2	None	4	2893130	165041	149730	4532847	0.85
2	None	4	4165672	175572	153002	5675345	1.16
2	None	4	3219226	152204	133575	4538156	0.91
2	None	6	1590984	80729	63836	2437991	0.46
2	None	6	2239800	89472	68575	3263163	0.65
2	None	6	1835386	78529	69570	2881732	0.54
2	None	6	1618693	75770	66880	2318061	0.46
3	None	2	30332469	1711137	454017	54671596	9.61
3	None	2	44031367	2170582	500735	61676013	11.88
3	None	2	29442344	1874613	385042	39998610	7.70
3	None	2	45415891	2205981	518822	64932968	11.19
3	None	4	10175908	530249	122924	16643242	2.87
3	None	4	12400658	550644	122178	18203244	3.52
3	None	4	9532757	523566	97705	13603293	2.82
3	None	4	9888071	458586	105954	15054874	2.87
3	None	6	7521442	264340	52001	9239090	1.78
3	None	6	5214422	255779	50336	7449463	1.54
3	None	6	6587549	297336	56059	10549366	1.76
3	None	6	8427241	281509	52675	9540413	2.08

Table 8: FNAD TLD readings. Readings have been ECC and RCF corrected. Fade was determined to be 0.81.

Irradiation	TLD Type	Reading (gU)
Shot 1	Li-6	6008209
Shot 1	Li-6	6850110
Shot 1	Li-7	53617
Shot 1	Li-7	105747
Shot 2	Li-6	2678501
Shot 2	Li-6	2476865
Shot 2	Li-7	62776
Shot 2	Li-7	89721
Shot 3	Li-6	8370393
Shot 3	Li-6	8303371
Shot 3	Li-7	187052
Shot 3	Li-7	257214

Table 9: FNAD dose results. All measurements were performed at 4 m.

Irradiation	Shield	Dose (Gy)
1	Pb	2.29
2	None	0.92
3	None	2.90

Table 10: Identifinder blood sodium detection results. Doses are based on the preliminary estimates and decay corrected for time post irradiation. “ni” indicates that Na-24 was not identified.

Date	Count Time	Count Duration (min.)	Decay Time (Hours)	Ident. Prob.	Estimated Dose (Gy)
10/13/2009	14:35	1	3.70	10	1.98
10/13/2009	14:40	2	3.78	10	1.97
10/13/2009	14:48	5	3.92	10	1.96
10/13/2009	14:50	1	3.95	10	1.96
10/13/2009	14:54	2	4.02	10	1.95
10/15/2009	14:04	1	51.18	8	0.22
10/15/2009	14:06	2	51.22	9	0.22
10/15/2009	14:12	5	51.32	9	0.22
10/15/2009	14:32	1	51.65	9	0.22
10/15/2009	14:35	2	51.70	9	0.22
10/16/2009	10:30	1	71.62	6	0.09
10/16/2009	10:30	2	71.62	8	0.09
10/16/2009	10:30	5	71.62	8	0.09
10/16/2009	10:45	0.25	71.87	5	0.08
10/16/2009	10:45	0.25	71.87	6	0.08
10/16/2009	10:50	0.5	71.95	5	0.08
10/16/2009	10:50	0.5	71.95	ni	0.08
10/16/2009	10:50	1	71.95	6	0.08
10/16/2009	10:55	1	72.03	5	0.08
10/15/2009	14:24	5	3.47	10	2.56
10/15/2009	14:27	2	3.52	10	2.55
10/15/2009	14:29	1	3.55	9	2.55
10/15/2009	14:30	1	3.57	9	2.54
10/16/2009	10:35	5	23.65	10	1.01
10/16/2009	10:35	2	23.65	9	1.01
10/16/2009	10:35	1	23.65	9	1.01
10/16/2009	10:40	1	23.73	9	1.00
10/16/2009	10:40	0.5	23.73	9	1.00
10/16/2009	10:40	0.25	23.73	8	1.00
10/16/2009	10:45	0.25	23.82	7	1.00

5 Discussion

A summary of the preliminary dose calculations is given in Table 11. The doses listed are the averages from the various irradiations and distances. During analysis it was noticed that for some irradiations and distances the variability in results was significant. During placement of dosimeters it was necessary to position phantoms at different rotational angles around the core. Thus, because of non-isotropic field effects, it is certainly possible that dose rates could vary significantly. The results for each distance were analyzed for minimum and maximum calculated doses. These are listed in Table 12.

Table 11: Preliminary dose summary for 2009 calculated with each of the various dosimeters.

TLD Type		Dist. (m)	Shot 1 (Gy)	Shot 2 (Gy)	Shot 3 (Gy)
Neutron	$D_p(10)$, Neutron	2 m	6.2	2.8	10.1
Neutron	$D_p(10)$, Neutron	4 m	2.3	1.0	3.0
Neutron	$D_p(10)$, Neutron	6 m	1.2	0.5	1.8
HBGT	$D_p(10)$, Neutron	2 m	8.0	3.4	11.2
HBGT	$D_p(10)$, Neutron	4 m	2.9	1.0	3.5
HBGT	$D_p(10)$, Neutron	6 m	1.6	0.6	2.2
HBGT	$D_p(10)$, Photon	2 m	1.8	3.3	9.3
HBGT	$D_p(10)$, Photon	4 m	0.8	1.1	2.8
HBGT	$D_p(10)$, Photon	6 m	0.5	0.5	1.6
Neutron & HBGT	$D_p(10)$, Total	2 m	8.0	6.1	19.4
Neutron & HBGT	$D_p(10)$, Total	4 m	3.1	2.1	5.8
Neutron & HBGT	$D_p(10)$, Total	6 m	1.7	1.0	3.4
HBGT	$D_p(10)$, Total	2 m	9.8	6.7	20.5
HBGT	$D_p(10)$, Total	4 m	3.7	2.1	6.3
HBGT	$D_p(10)$, Total	6 m	2.1	1.1	3.8
FNAD	D*(10), Neutron	4 m	2.3	0.9	2.9

It is encouraging that the FNAD results are in agreement with the whole body dosimeters. This is significant since the FNADs were developed and tested using two configurations of a ^{252}Cf source (unmoderated intended to approximate a metal criticality spectrum and polyethylene moderated to approximate a solution assembly).

The neutron to gamma dose ratios for the 2009 test are in reasonable agreement for the unshielded reactor. However, the neutron to gamma ratios for the lead shielded reactor differ significantly. These ratios are listed in Table 13.

The spectral correction factors listed in Table 5 were determined based on the 2002 data measured at 4m. As the neutrons exit the reactor core the spectrum begins to soften due to room and air scatter effects. Additionally, during testing there were a number of phantoms in the room which further contributed to scatter and thermalization. There was an indication that the neutron fluence and energy was not isotropic with regards to rotation about the room. Referring to Figure 1 phantoms were placed primarily in the direction of the largest floor area of the room (i.e. near reference point 7). However, because of the large number of dosimeters being irradiated it was necessary to place some dosimeters on the opposite side of the reactor where the distance to the nearest wall is smaller. This would likely result in increase thermalization of the field due to room return. It was noticed during analysis of the results that on some irradiations a significant difference in calculated dose values was evident. During each of the three irradiations a set of two beta/gamma and two neutron TLDs were placed in reference position 5 per Figure 1. A second set of two beta/gamma and two neutron TLDs were positioned at a location on the lower right side of the reactor according to Figure 1. Significant differences in the calculated neutron and photon doses were observed between these locations. Table 14 lists the calculated doses and standard deviations of the average of the entire 2 m data set and the averages and standard deviations of the TLDs by irradiation location.

The Identifinder performed well and the minimum detectable dose (MDD) values appear to coincide with those provided in Reference [10]. From the preliminary dose estimates the MDD is less than 10 rad for solution criticalities. It is unfortunate that no G-M measurements could be performed due to time constraints and shipping limitations. The initial dose estimate based on the MDA of the Identifinder was reasonably close for the first irradiation, although the instrument is not intended for this purpose but instead to give an indication of general level of exposure.

Table 12: Preliminary dose summary analysis for 2009 calculated with the whole body dosimeters. Average, minimum, and maximum doses for each irradiation and distance are listed.

$H_p(10)$ Neutron (Gy) Neutron TLD			
	Shot 1	Shot 2	Shot 3
2 m Avg.	6.2	2.8	10.1
2 m Min.	5.3	2.3	7.7
2 m Max.	7.1	3.5	11.9
4 m Avg.	2.3	1.0	3.0
4 m Min.	2.2	0.8	2.8
4 m Max.	2.6	1.2	3.5
6 m Avg.	1.2	0.5	1.8
6 m Min.	1.1	0.5	1.5
6 m Max.	1.4	0.6	2.1
$H_p(10)$ Neutron (Gy) HBGT TLD			
	Shot 1	Shot 2	Shot 3
2 m Avg.	8.0	3.4	11.2
2 m Min.	6.8	2.7	9.9
2 m Max.	10.7	4.9	12.6
4 m Avg.	2.9	1.0	3.5
4 m Min.	2.4	0.9	3.0
4 m Max.	3.3	1.3	4.1
6 m Avg.	1.6	0.6	2.2
6 m Min.	1.5	0.5	1.9
6 m Max.	1.7	0.7	2.4
$H_p(10)$ Photon (Gy)			
	Shot 1	Shot 2	Shot 3
2 m Avg.	1.8	3.3	9.3
2 m Min.	1.6	3.2	8.8
2 m Max.	2.0	3.3	9.6
4 m Avg.	0.8	1.1	2.8
4 m Min.	0.7	1.0	2.7
4 m Max.	1.0	1.2	2.9
6 m Avg.	0.5	0.5	1.6
6 m Min.	0.4	0.5	1.5
6 m Max.	0.6	0.6	1.7

Table 13: Neutron to gamma dose ratios for 2002 and 2009. The neutron doses include contributions from photons produced via (n,γ) reactions in the phantom. 2002 ratios are based on the reference doses. 2009 values are based on the doses at 4 m.

2002			
	Shot 1	Shot 2	Shot 3
	Bare	Pb	Pb
D_n:D_γ	0.95	8.0	7.9
2009, Neutron and HBGT TLDs			
	Shot 1	Shot 2	Shot 3
	Pb	Bare	Bare
D_n:D_γ	2.92	0.89	1.07
2009, HBGT TLDs			
	Shot 1	Shot 2	Shot 3
	Pb	Bare	Bare
D_n:D_γ	3.63	0.91	1.25
	Pb	Bare	
2002 Avg.	8.0	0.95	
2009 Avg. (Neutron & HBGT)	2.9	0.98	
2009 Avg. (HBGT)	3.6	1.08	

Table 14: Evidence of potential non-isotropic dose rates. Group A is located near reference point 7 per Figure 1 and group B is located to the lower right with regards to Figure 1. All TLDs were positioned a distance of 2 m from the reactor.

Neutron TLD			
	Shot 1	Shot 2	Shot 3
All TLD Avg. D_n (Gy)	6.2	2.8	10.1
All TLD %σ D_n	15.7	19.0	18.4
Group A Avg. D_n (Gy)	7.0	3.2	11.5
Group A %σ D_n	2.9	12.6	4.8
Group B Avg. D_n (Gy)	5.3	2.4	8.7
Group B %σ D_n	0.6	6.9	15.6
HBGT TLD			
	Shot 1	Shot 2	Shot 3
All TLD Avg. D_n (Gy)	8.0	3.4	11.2
All TLD %σ D_n	23.2	30.0	11.3
Group A Avg. D_n (Gy)	9.0	4.1	12.3
Group A %σ D_n	26.5	29.6	3.2
Group B Avg. D_n (Gy)	6.9	2.8	10.2
Group B %σ D_n	1.8	4.4	3.9
HBGT TLD			
	Shot 1	Shot 2	Shot 3
All TLD Avg. D_γ (Gy)	1.8	3.3	9.3
All TLD %σ D_γ	10.9	1.1	3.7
Group A Avg. D_γ (Gy)	1.9	3.3	9.5
Group A %σ D_γ	3.7	0.8	1.9
Group B Avg. D_γ (Gy)	1.6	3.3	9.1
Group B %σ D_γ	2.5	0.8	4.1

6 Results from 2009 Testing

Reference doses for each of the irradiations were provided by the Silene staff. These are summarized in Table 15

Table 15: Silene-reported delivered doses.

Dose	Dist.	Shot 1	Shot 2	Shot 3
Neutron	2 m	6.9	3.2	9.7
Neutron	3 m	3.2	1.6	4.8
Neutron	4 m	1.9	0.9	2.9
Neutron	6 m	1.1	0.5	1.5
Photon	2 m	0.5	3.8	12.0
Photon	3 m	0.4	2.0	6.1
Photon	4 m	0.3	1.3	3.8
Photon	6 m	0.2	0.7	2.1
Fissions ($*10^{17}$)		1.77	0.63	1.90

The bias for the calculated values are listed in Table 16 for each of the dosimeter types.

Table 16: Comparison of calculated and reported delivered doses.

		Shot 1			Shot 2			Shot 3		
		Silene-Reported (Reference)								
	Dose	2 m	4 m	6 m	2 m	4 m	6 m	2 m	4 m	6 m
Reference	Neutron	6.9	1.9	1.1	3.2	0.9	0.5	9.7	2.9	1.5
Reference	Photon	0.5	0.3	0.2	3.8	1.3	0.7	12.0	3.8	2.1
		Y-12 Reported								
TLD	Dose	2 m	4 m	6 m	2 m	4 m	6 m	2 m	4 m	6 m
Neutron	Neutron	6.2	2.3	1.2	2.8	1.0	0.5	10.1	3.0	1.8
HBGT	Neutron	8.0	2.9	1.6	3.4	1.0	0.6	11.2	3.5	2.2
HBGT	Photon	1.8	0.8	0.5	3.3	1.1	0.5	9.3	2.8	1.6
FNAD	Neutron	–	2.3	–	–	0.9	–	–	2.9	–
		Bias (%)								
Neutron	Neutron	-10.1	21.1	9.1	-12.5	11.1	0.0	4.1	3.4	20.0
HBGT	Neutron	15.9	52.6	45.5	6.2	11.1	20.0	15.5	20.7	46.7
HBGT	Photon	260.0	166.7	150.0	-13.2	-15.4	-28.6	-22.5	-26.3	-23.8
FNAD	Neutron		21.1		–	0.0	–	–	0.0	–

The calculated results for neutron dose computed using the neutron TLDs are in good agreement with the reference values. The neutron doses calculated from the FNAD are in excellent agreement. Neutron doses computed using the HBGT dosimeter (simulating the Y-12 PNAD) were reasonable given the single neutron-sensitive, however a slight correction to the SCF may be in order. Further analysis of the TLD results are needed, particularly a comparison between the response of the non-cadmium covered element in the neutron dosimeter with the HBGT neutron sensitive element since the responses of these should be similar.

The HBGT TLD performed well for unshielded irradiations. In the single lead-shielded irradiation, however, the performance was unacceptable. No immediate cause for this poor performance is understood. A comparison with other participants may yield some insight.

7 Conclusions

The testing at Silene has proven very useful. The performance testing from 2002 with regards to bias in dose was not encouraging, but did provide essential data towards refining the correction factors applied to TLD results. Recommendations for future tests include:

- It would be beneficial to perform irradiations at both Silene and Caliban. The neutron spectra, fluence, and neutron to photon dose ratios are radically different since Silene is a solution assembly and Caliban is metal. These would provide excellent "default" choices for first pass dose estimates without additional spectral information for facilities based on criticality type.
- It would be useful to continue and expand blood sodium experiments using more phantom irradiations and instrumentation.
- Additional triage-style experiments could be performed such as coin, jewelry, hair, etc. activation.
- Test and evaluate the performance of electronic dosimeters.
- Examine the impact of rotation on the dosimeter performance.
- Evaluate the feasibility of using the activated copper filter in the beta/gamma TLD holders as a screening tool to determine necessary TLD reader filtration.
- If possible, it would be desirable to gain measurement information on shielding effects of various materials by placing representative samples in front of sets of dosimeters.
- Measuring the dose in air (rad in air) used by criticality safety to determine alarm zones since this quantity has been shown to have little relation to the absorbed dose in tissue [13].
- Based on the reference values of the 2009 irradiations, modifications to the spectral correction factors for the beta/gamma, neutron, and FNAD TLDs can be implemented. Additionally, correction factors to convert signal to gamma dose can be determined for both the HBGT and the neutron TLDs.

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